The cavitation flow in the jet pump cavitation reactor and its sterilization of *E. coli*

[1,2]Jiong Wang; [1,2]Xinping Long*; [3]Junqiang Zhang; [3]Longzhou Xiao; [1,2]Bin Ji;
[1] *Hubei Key Laboratory of Waterjet Theory and New Technology, Wuhan University, Wuhan 430072, China;*
[2] *School of Power and Mechanical Engineering, Wuhan University, Wuhan 430072, China;*
[3] *Wuhan Second Ship Design and Research Institute, Hubei, 430064 China*

Abstract
In the present paper, experiments are conducted to investigate the effects of a jet pump cavitation reactor (JPCR) on the sterilization of *e. coli*. The basic performance of the JPCR is tested firstly. And then the sterilization influences of cavitation state and initial bacterial concentration are investigated. The results show that the cavitation in the JPCR has satisfying effects on *e. coli* sterilization. With the decrease of pressure ratio, flow ratio increases and reaches a maximum value, which is so-called limited operation cavitation stage. In this stage, severe cavitation occurs, which is used to sterilize *e. coli* in this paper. Generally speaking, as the treating time increases, sterilization rate increases slowly at first, and then surges. This hysteresis effect indicates that *e. coil* shows resistance in a short time with the explosure to cavitation. The unsteady cavitation oscillating in throat can provide a better sterilization effect. Moreover, with the decrease of initial bacteria concentration, the sterilization rate increase. Our work provides a new method of sterilization with great potentiality.

Keywords: cavitation; jet pump cavitation reactor; *e. coli*; sterilization effect

1. Introduction

Cavitation is a phase transition between liquid and vapor occurring within the liquid inside or at the liquid-solid interface because of the power in the flow [1]. Cavitation nearly occurs in all kinds of fluid machinery and generates undesirable effects such as noise, vibration, material damage and performance reductions [2-4]. But in fact, cavitation is not entirely harmful. The local high temperature, high pressure, microjet, shock wave and the free radicals induced by the cavitation bubble can build special reaction site [5-7]. This favorable effect can be used in food engineering, bioengineering, mining industry and sewage treatment [8-10], etc.

There have many studies on cavitation applications. Ultrasonic cavitation is the most commonly used but it has high energy costs. Hydraulic cavitation has wide application prospect because of simple structure, high efficiency and good economy. The hydraulic cavitation reactors is various, such as orifice, venture, high pressure homogenizer and high speed homogenizer. Many studies have been conducted to investigate the application of cavitation reactors. Jyoti's [11] experiments shows that the hybrid technique combined hydrodynamic cavitation appears to be an attractive alternative to a single technique for the reduction in the heterotropic plate count bacteria. Balasundaram [12] carries out the disruption of *e. coli* by orifice plate for the purpose of preferentially releasing the intracellular proteins from organisms. Shivram [13] carries out the seawater disinfection using cavitation produced by vortex diode and have proved its effectiveness in killing of various types of zooplanktons in the seawater. These researches are satisfying and promising in sterilization application but further investigate is needed in hydraulic cavitation method. JPCR is a kind of cavitation reactor combining the feature of orifice and venture. Because of high velocities gradient and severe shear flows in JPCR, cavitation occurs easily, so it is of high potential in sterilization. However, relative investigations are rarely reported.

Therefore, experiments are conducted to obtain more understanding of cavitation flow in JPCR and its sterilization effect in the current paper. The basic performance of JPCRs is tested and the corresponding sterilization experiments are also conducted to study the influence of the cavitation state and initial bacterial concentration on sterilization effect.

2. Experiment Setup

2.1 *The structures of JPCR*

The structure of a typical JPCR is shown in **Fig. 1.** The main structure parameters are set as follows: inlet pipe diameter, D_{in}=25mm; outlet pipe diameter, D_{out}=50mm; throat length, L_{th}=96mm; contraction angle, α=45deg; and diffuser angle, β=12deg. Since JPCRs with the same area ratio (throat to the nozzle exit area ratio) have similar performance, three area ratios are obtained by only altering the size of the nozzle but fixing the sizes of the throat and the other parts for the convenience of machining. In this paper, the nozzle outlet diameters, D_n=8, 10, 12mm are employed to obtain three area ratios 4.00, 2.56, 1.78.

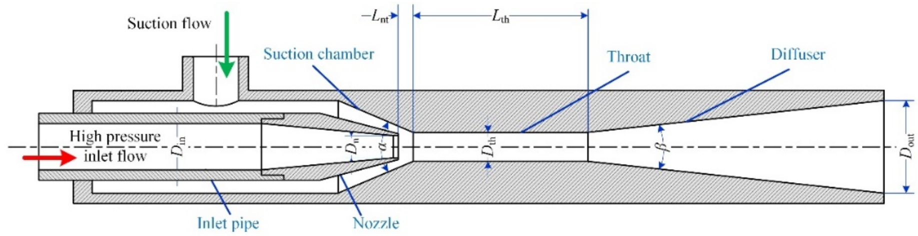


Fig. 1 Schematic drawing of JPCR

The basic performance of a JPCR can be characterized by the classical parameter such as area ratio (*m*), flow ratio (*q*) and pressure ratio (*h*). All these dimensionless parameters are defined as follows,

$$m = \frac{A_{th}}{A_n} \tag{1}$$

$$q = \frac{Q_s}{Q_{in}} \tag{2}$$

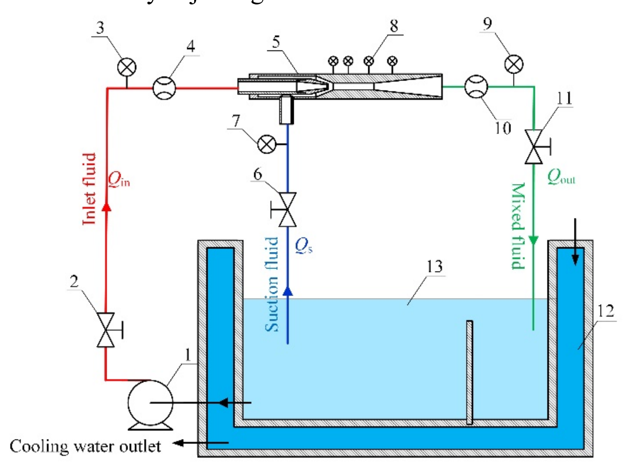
$$h = \frac{P_{out} - P_s}{P_{in} - P_s} = \frac{\left(\frac{p_{out}}{\rho_{out} g} + \frac{v_{out}^2}{2g} + z_{out}\right) - \left(\frac{p_s}{\rho_s g} + \frac{v_s^2}{2g} + z_s\right)}{\left(\frac{p_{in}}{\rho_{in} g} + \frac{v_{in}^2}{2g} + z_{in}\right) - \left(\frac{p_s}{\rho_s g} + \frac{v_s^2}{2g} + z_s\right)} \tag{3}$$

where *A* represents the cross sectional area, *Q* represents the flow rate, *ρ* represents the density, *P* represents the total pressure, *p* represents the hydrostatic pressure, *z* represents the elevation, *v* represents the average velocity of flow, respectively. Subscript in, th, n, s, out represent inlet fluid, throat inlet, nozzle exit, suction fluid, outlet fluid respectively.

2.2 *Experiment rig and procedure*

The experimental rig is illustrated in **Fig. 2.** The high pressure inlet flow (Q_{in}) supplied by a centrifugal pump entrains the suction flow (Q_s) from the water tank. The high pressure inlet flow and the suction flow mixes in the nozzle outlet and induces strong shear cavitation, the mixed flow run through the throat. The inlet and mixed flow rates are controlled by valves and measured by electromagnetic flow meters. Three pressure transducers are installed in the main water flow inlet, the suction pipe inlet and the diffuser outlet.

Because of high speed gradient and shear flows in throat, the cavitation develops violently and a large number of cavitation bubbles occurs, which collapse when passing through the diffuser due to high back pressure. In addition, different cavitation state can be obtained by adjusting the outlet valve 11.



1-centrifugal pump; 2,6,11-valves; 4,10-electromagnetic flowmeter;
3,7,8,9-pressure sensor; 5-JPCR; 12-cooling water tank; 13-water tank

Fig. 2 Sketch of the experimental rig

The treatment of bacteria solution with different initial bacterial concentration was carried out by JPCRs at different cavitation state. For all the tested experiments, fixed treating fluid volume of 60L and a circulation time through the device of 3-4 hours was maintained. In all the treating conditions, the cooling water tank was open to keep the water temperature constant (20-30℃). Samples were taken at regular intervals and the concentration of bacterium was measured by plate count method. The disinfection rate (γ) was calculated as follow,

$$\gamma = \left(1 - \frac{N_1}{N_0}\right) \times 100\% \qquad (4)$$

where N_0, N_1 represents the concentration of live bacteria before and after treatment.

3. Result and discussion

Before the sterilization experiment, some check experiment was carried out. The results shows that the concentration of live bacteria didn't change under no cavitation stage and tested water temperature. So the death of bacteria is caused by cavitation.

3.1 *Basic performance of JPCR*

Fig. 3 shows the basic performance of JPCRs. Under different pressure ratios, the cavitation state changes significantly. With the decrease of pressure ratio (h), flow ratio (q) increases gradually. The maximum q is then the so-called cavitating flow ratio, q_c. The corresponding flow condition is defined as the limited operation stage. Severe cavitation occurs during this stage with massive cavity clouds completely filling the throat and even expanding into the diffuser when h is very low. The cavitation flow chokes the flow at the throat and the velocity may reach the sound velocity, so q remains almost constant with further decrease of p_{out}. In current paper, the limited cavitation stages are used for sterilization. Below the cavitating flow ratio, the h-q curves overlap for the same area ratio but different inlet pressures. Smaller area ratios result in steeper performance curves. However, during the limited operation stage, the curves separate and become vertical with different q_c for different p_{in} and a smaller area ratio leading to a smaller q_c, which means that JPCRs with small area ratio can more easily reach the limiting condition. As the flow ratio decreases from the maximum, the cavitation weakens and finally disappears.

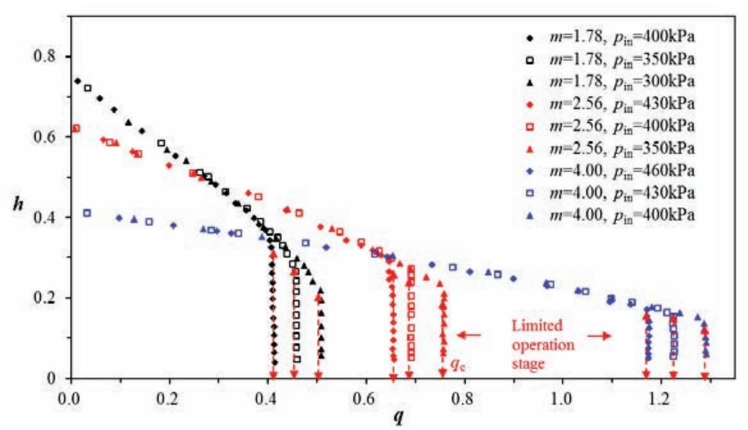


Fig. 3 The basic performance of JPCR

3.2 *The sterilization effect under different cavitation state*

Fig. 4 shows the sterilization effect under different cavitation state in limited cavitation stage. It can be seen that the sterilization rate gradually increase with increasing treating time. The sterilization rate is lower within the former 30 min. However, the sterilization rate significantly increased at 60 min, and then it slows down and gets close to 100% at 150 min. It indicated that the cavitation of JPCR has satisfying effect on *e. coli*, but there exists hysteresis effect. *E. coli* cannot be killed immediately unless damage accumulates to a certain degree, at this time the sterilization rate increases significantly. But the sterilization speed is different in different treatment conditions although the change rules are consistent. It can be seen that the sterilization rate in stable limited operation cavitation stage (the collapse position is in the diffuser) is much lower than that in unstable limited operation cavitation stage (the collapse position is in the throat). With the increase of pressure ratio, the back pressure increases and cavitation area shrinks. The cavitation clouds switch from stable development to unstable pulsation in throat. As a result, the corresponding sterilization rate increase. That is to say, the bactericidal effect is not determined solely by the number of cavitation bubbles, but also depends on the back pressure and pulsating pressures of the environment. In unstable limited operation cavitation stage, the cavitation cloud chokes the flow in the throat with greater pressure pulsation than stable limited operation cavitation stage. And the *e. coli* was killed quickly under high frequency pulsating pressures.

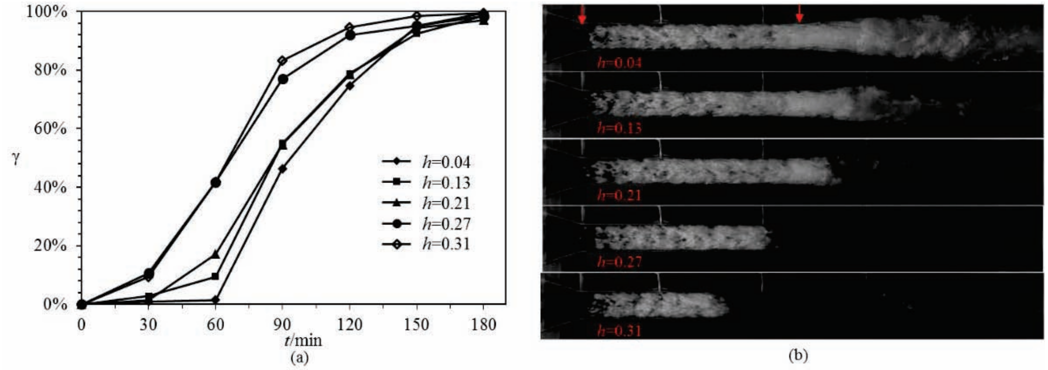


Fig. 4 The sterilization effect under different cavitation state (m=1.78, p_{in}=400kPa)

3.3 *The sterilization effect under different initial bacterial concentration*

Fig. 5 shows the sterilization effect under different initial bacterial concentration. It can be seen that the change rule of sterilization rate is the same for different initial bacterial concentration. But with the decrease of initial bacterial concentration, the sterilization rate increase significantly. The lower the initial bacterial concentration is, the faster the sterilization speed is. In the lower initial bacterial concentration, the number of bacteria treated with cavitation is less and the cumulative time of damage is shorter, so the corresponding effects of sterilization rate and treating time is much greater.

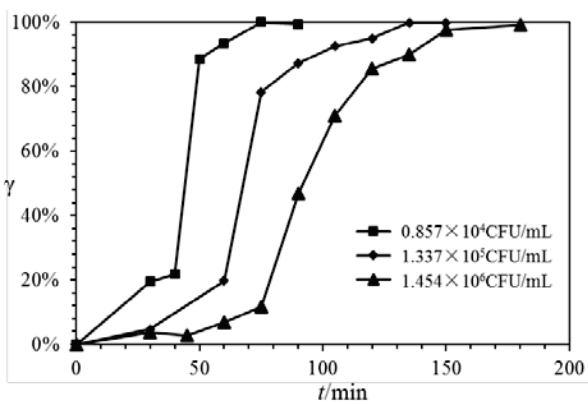


Fig. 5 The sterilization effect under different initial bacterial concentration (m=2.56, h=0.20).

4. Conclusions

In this paper, the basic performances of JPCRs are investigated and the corresponding sterilization experiments are also conducted to study the influence of the cavitation state and initial bacterial concentration on sterilization effect. The main conclusions can be draw as follows,

(1) As pressure ratio decreases, flow ratio reaches a maximum value and cavitation gets severer, the cavitation in JPCR reaches the limited cavitation stage with massive cavitation bubbles when flow ratio increases to the maximum value. And the severe cavitation is the applied sterilization conditions;

(2) The cavitation of JPCR has satisfying effect on *e. coli*, but there exists hysteresis effect. *E. coli* cannot be killed immediately unless damage accumulates to a certain degree for long time;

(3) The sterilization effect can be improved by adjusting pressure ratio to make the cavitation state switch from stable limited cavitation stage to unstable limited cavitation stage. The cavitation effects in the throat is stronger than that in the diffusor. Moreover, with the increase of concentration of initial bacteria, the sterilization rate decreases.

Acknowledgements

This work was financially supported by the National Natural Science Foundation of China (Project Nos. 11472197, 51679169 and 51576143).

References

[1] Pan, S., Peng, X. (2013). *Physical Mechanism of Cavitation*. National Defence Industry Press.
[2] Korkut, E., Atlar, M. (2012). *An experimental investigation of the effect of foul release coating application on performance, noise and cavitation characteristics of marine propellers*. Ocean Engineering, 41(1).
[3] Wittekind, D., Schuster, M., (2016). *Propeller cavitation noise and background noise in the sea*. Ocean Engineering. 120.
[4] Shi, W., Atlar, M., Rosli, R., et al., (2016). *Cavitation observations and noise measurements of horizontal axis tidal turbines with biomimetic blade leading-edge designs*. Ocean Engineering. 121.
[5] Suslick, K.S., (1989). *The Chemical Effects of Ultrasound.* Scientific American. 260.
[6] Mason, T.J., Lorimer, J.P., (2002). *Applied Sonochemistry: Uses of Power Ultrasound in Chemistry and Processing*.
[7] Badve, M., Gogate, P., Pandit, A.B., et al., (2013). *Hydrodynamic cavitation as a novel approach for wastewater treatment in wood finishing industry*, Separation & Purification Technology, 106(6).
[8] Gogate, P.R., Kabadi, A.M., (2009). *A review of applications of cavitation in biochemical engineering/biotechnology*. Biochemical Engineering Journal. 44(1).
[9] Gogate, P.R. (2010). *Hydrodynamic Cavitation for Food and Water Processing*. Food and Bioprocess Technology, 4(6).
[10] Save, S.S., Pandit, A.B., Joshi,J.B., (1997) *Use of Hydrodynamic Cavitation for Large Scale Microbial Cell Disruption*. Food and Bioproducts Processing. 75(1).
[11] Jyoti, K.K., Pandit, A.B., (2003). *Hybrid cavitation methods for water disinfection*. Ultrasonics sonochemistry. 14(1).
[12] Balasundaram, B., Harrison, S.T., (2006). *Study of physical and biological factors involved in the disruption of E. coli by hydrodynamic cavitation*. Biotechnology progress. 22(3).
[13] Sawant, S.S., Anil, A.C., Krishnamurthy, V., et al., (2008). *Effect of hydrodynamic cavitation on zooplankton:A tool for disinfection*. Biochemical Engineering Journal, 42(3).